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Cen A as TeV γ-ray and possible UHE cosmic-ray source

F.M. Rieger[1,2] and F.A. Aharonian[1,3]

[1] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany; e-mail: `frank.rieger@mpi-hd.mpg.de`
[2] European Associated Laboratory for Gamma-Ray Astronomy, jointly supported by CNRS and MPG
[3] Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin 2, Ireland

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ABSTRACT

Context. The most nearby active galaxy Cen A has attracted considerable attention as a detected TeV gamma-ray and possible ultra-high energy (UHE) cosmic-ray emitter.
Aims. We investigate the efficiency of particle acceleration close to the supermassive black hole (BH) horizon assuming that accretion in the innermost part of the disk occurs in an advection-dominated (ADAF) mode.
Methods. We analyze the constraints on the achievable particle energies imposed by radiative losses and corotation for conditions inferred from observations.
Results. We show that for an underluminous source such as Cen A, centrifugally accelerated electrons may reach Lorentz factors of up to $\gamma \sim (10^7 - 10^8)$, allowing inverse Compton (Thomson) upscattering of ADAF sub-mm disk photons into the TeV regime with an associated maximum (isotropic) luminosity of the order of a few times 10^{39} erg/s. Upscattering of Comptonized disk photons is expected to lead to a TeV spectrum $L_\nu \propto \nu^{-\alpha_c}$ with a spectral index $\alpha_c \simeq (1.5-1.9)$, consistent with H.E.S.S. results. The corresponding minimum variability timescale could be as low as $r_L/c \sim 1$ hr for a typical light cylinder radius of $r_L \simeq 5\,r_s$. While efficient electron acceleration appears to be well possible, protons are unlikely to be accelerated into the extreme UHECR regime close to the central black hole. We argue that if Cen A is indeed an extreme UHECR emitting source, then shear acceleration along the kpc-scale jet could represent one of the most promising mechanisms capable of pushing protons up to energies beyond 50 EeV.

Key words. galaxies: active – galaxies: jets – radiation mechanism: non-thermal – gamma rays: theory – individual: Cen A

1. Introduction

Centaurus A (NGC 5128, Cen A) is the closest (distance $d \sim 3.4$ Mpc; Israel 1998) and one of the best studied active galaxies. Optically, Cen A is an elliptical galaxy undergoing late stages of a merger event with a small spiral galaxy. Radio observations detected a complex FR I morphology with a subparsec-scale jet and counter-jet, a one-sided kiloparsec-scale jet, two radio lobes and extended diffusive emission. VLBI observations of the subparsec-scale jet indicate that Cen A is a non-blazar source with a jet inclination angle $i \gtrsim 50°$ (Tingay et al. 1998), or perhaps somewhat smaller if large-scale observations are reliable tracers (Hardcastle et al. 2003). The center of its activity is a supermassive black hole (BH) with a mass inferred to be in the range $m_{BH} \simeq (0.5 - 1.2) \times 10^8 M_\odot$ (Marconi et al. 2006; Häring-Neumayer et al. 2006), corresponding to a Schwarzschild scale $r_s \simeq (1.5 - 3.6) \times 10^{13}$ cm.
Cen A is the only AGN of the non-blazar type detected at MeV (COMPTEL: Steinle et al. 1998) and GeV energies (EGRET: Sreekumar et al. 1999). The nuclear spectral energy distribution (SED) of Cen A, as inferred from non-simultaneous data, appears to consist of two peaks, one reaching its maximum at several times 10^{13} Hz and one peaking around 0.1 MeV (Chiaberge et al. 2001; Meisenheimer et al. 2007). The SED below 1 GeV has been successfully modeled within a simple jet synchrotron self-Compton (SSC) framework, assuming Cen A to be a mis-aligned BL Lac object (Chiaberge et al. 2001). In the early days of gamma-ray astronomy, a tentative detection ($> 4\sigma$) of Cen A

at very high energies > 0.3 TeV was reported during a phase of high X-ray activity in 1972-1974 (Grindlay 1975). H.E.S.S. results (Aharonian et al. 2009a) have established Cen A as a TeV emitting source (the second radio galaxy after M87) with integral VHE flux of $\sim 1\%$ of the Crab Nebula.
Chandra and XMM-Newton observations between 2 and 7 keV indicate that the nuclear X-ray continuum spectrum in Cen A may consist of both a disk and a jet component, the disk contribution being consistent with a hybrid disk configuration where a standard disk is truncated at r_t and replaced by an ADAF in the inner regions close to the central black hole (Evans et al. 2004; cf. also Pellegrini et al. 2005 and Meisenheimer et al. 2007). A transition to an inner ADAF disk could also explain the lack of a big blue bump UV feature expected in the standard disk scenario (Marconi et al. 2001). The accretion rate for Cen A seems uncertain by about an order of magnitude, with model-dependent estimates ranging from several 10^{-4} to some $10^{-3}\,\dot{m}_{Edd}$. Taking the measured nuclear X-ray luminosity of $L_x \sim 5 \times 10^{41}$ erg/s (Evans et al. 2004) as a robust upper limit to a possible ADAF disk contribution gives $\dot{m} \lesssim 0.004\dot{m}_{Edd}$, which for the canonical viscosity parameter $\alpha \simeq 0.3$ is still below the critical mass accretion rate $\dot{m}_{crit} \simeq 0.3\,\alpha^2\,\dot{m}_{Edd}$ required for a two-temperature ADAF to occur (Narayan et al. 1998; Yi 1999).
If the first SED peak below 10^{14} Hz is indeed caused by synchrotron emission from the jet (Chiaberge et al. 2001; Meisenheimer et al. 2007), inverse Compton upscattering in a conventional homogeneous SSC framework is unable to account for VHE γ-rays in the TeV regime. On the other hand, it could be that the situation for Cen A is similar to that for M 87, where

efficient particle acceleration close to the BH horizon seems to be responsible for the production of the observed TeV γ-rays (Aharonian et al. 2009b; Rieger & Aharonian 2008a, henceforth: RA08a). Here we analyze possible VHE characteristics associated with this scenario. We show that for parameters inferred from observations, inverse Compton upscattering of ADAF disk photons by centrifugally accelerated electrons could result in variable ($\sim$ 1 hr) VHE γ-rays with a relatively hard TeV spectrum. We show that the mechanism considered is unable to accelerate protons to ultra high energy cosmic-ray (UHECR) energies, although shear acceleration along the jet could potentially provide a means.

2. Cen A as a TeV γ-ray source

2.1. Particle acceleration close to the BH horizon

Magnetic fields are widely considered to play a key role in the formation of collimated relativistic outflows from compact objects. According to, e.g., MHD scenarios, magnetic flux dragged in by the accretion flow and suitably amplified by dynamo actions in the inner accretion disk can build up a rigidly rotating (quasi-dipolar) disk magnetosphere. Depending on the field-line rotation and the current distribution, the bulk of the plasma may then be centrifugally accelerated along open flux surfaces to relativistic speeds ($\Gamma_b \sim 10$) and become collimated outside the light cylinder $r_{\rm L} \simeq (5-10)\, r_s$ (e.g., Camenzind 1995; Fendt 1997). In what follows, we explore an approach where efficient particle acceleration is supposed to occur close to the light cylinder (e.g., Machabeli & Rogava 1994; Gangadhara & Lesch 1997; Rieger & Mannheim 2000; Osmanov et al. 2007). Within the MHD framework this could occur if, e.g., the longitudinal current becomes smaller than a critical value (Beskin & Rafikov 2000). Let us suppose, thus, that a significant fraction of the electromagnetic energy may be transformed into the kinetic energy of particles by means of magneto-centrifugal effects close to $r_{\rm L}$. Consider for illustration a charged test particle, corotating with the magnetic field and gaining energy while moving outwards (Machabeli & Rogava 1994). The motion of this particle may be analyzed conveniently in the framework of Hamiltonian dynamics: For length scales much smaller than the curvature radius of the field, the field topology is monopole-like and the associated Hamiltonian H for a particle of rest mass m_0 moving along a relativistically, rigidly rotating field-line (angular velocity $\Omega = c/r_{\rm L}$ = constant) becomes a constant of motion

$$H = \gamma\, m_0\, c^2 (1 - r^2/r_{\rm L}^2) = {\rm const.}\,, \tag{1}$$

where $\gamma = (1 - r^2/r_{\rm L}^2 - \dot{r}^2/c^2)^{-1/2}$ is the particle Lorentz factor. Thus, as a particle approaches $r_{\rm L}$, its Lorentz factor might increase dramatically (provided corotation holds; however, it cannot become infinite, see below). Using Eq. (1) and the definition of γ, this can be expressed in terms of a characteristic (minimum) acceleration timescale (cf. RA08a)

$$t_{\rm acc} = \frac{\gamma}{\dot{\gamma}} \simeq \frac{1}{2\,\Omega\,\tilde{m}^{1/4}\gamma^{1/2}}\,, \tag{2}$$

valid for $\gamma \gg 1$, where $\tilde{m} = 1/(\gamma_0^2\,[1 - r_0^2/r_{\rm L}^2]^2)$ depends on the initial injection conditions.

2.2. Constraints on achievable Lorentz factors

Under realistic astrophysical conditions, the acceleration efficiency is constrained by radiation reaction (e.g., inverse Compton in the ambient photon field), the breakdown of the bead-on-the-wire (BW) approximation for a single particle or the bending of the field line with increasing inertia. For a mass accretion rate in the concordant range $(2-20) \times 10^{-4} \dot{m}_{\rm Edd}$ (e.g., Marconi et al. 2001; Evans et al. 2004; Pellegrini 2005; Meisenheimer et al. 2007), the ADAF equipartition magnetic field $B_{\rm eq} \propto m_{\rm BH}^{-1/2} r^{-5.4} \dot{m}^{1/2}$ (Yi 1999) becomes $B_{\rm eq}(3\,r_s) \gtrsim 500$ G, suggesting (radial) jet magnetic field strengths near the light cylinder of $B(r_{\rm L}) \gtrsim 50$ G. In the case of BL Lac objects, transition radii from tens to several hundred r_s have been inferred from observations (e.g., Cao 2003; Wu & Cao 2005). Similarly, the apparent lack of a standard disk feature in the observed SED of Cen A seems to indicate as well that $r_t > 10\, r_s$. By assuming that all of the measured X-ray luminosity in Cen A of $L_x \sim 5 \times 10^{41}$ erg/s is produced by an inner ADAF, the implied energy densities is $U_{\rm ph} \sim L_x/(4\pi\, r_t^2 c) \lesssim 1$ erg/cm^3 for $r_t \gtrsim 30\, r_s$. A similar constraint might be obtained based on the ADAF synchrotron peak luminosity $L_R \sim \nu_s L_{\nu_s} \propto m_{\rm BH}^{6/5} \dot{m}^{4/5} \nu_s^{7/5}$ (Yi 1999) close to $r_{\rm L}$, where $\nu_s(r_{\rm L}) \simeq 7 \times 10^{11}$ Hz, which give $L_R \sim 3 \times 10^{39}$ erg/s, using the fiducial parameters $\dot{m} = 5 \times 10^{-4} \dot{m}_{\rm Edd}$, $m_{\rm BH} = 10^8 M_\odot$, and $r_{\rm L} \sim 5\, r_s$ (giving $B(r_{\rm L}) \sim 100$ G), implying a photon energy density $U_{\rm ph} \sim 0.4$ erg/cm^3.

(i) Inverse Compton losses (Thomson regime) for electrons, occurring on timescales of $t_{\rm cool} \simeq 3 \times 10^7/[\gamma\, U_{\rm ph}]$ s, then imply (see Eq. (2)) that achievable electron Lorentz factors are limited to

$$\gamma_{\rm max,e}^{\rm IC} \simeq 3 \times 10^8\, \sqrt{\tilde{m}}\, \left(\frac{10^{14}{\rm cm}}{r_{\rm L}}\right)^2 \left(\frac{1\ {\rm erg/cm}^3}{U_{\rm ph}}\right)^2. \tag{3}$$

(ii) For motion along the field synchrotron losses are negligible, while curvature losses, occurring on characteristic timescales of $t_c \simeq 180\, R_c^2 (m_0/m_e)\, \gamma^{-3}$, do not impose stronger constraints (compared to Eq. (3)) for curvature radii $R_c \sim r_{\rm L}$.

(iii) The validity of the BW approximation for protons, on the other hand, requires that their characteristic acceleration timescale is always longer than the inverse of the relativistic gyro-frequency (cf. Rieger & Aharonian 2008b), which constrains the achievable proton Lorentz factors to be

$$\gamma_{\rm max,p}^{\rm BB} \simeq 10^6\, \tilde{m}^{-1/6} \left(\frac{B(r_{\rm L})}{50\,{\rm G}}\right)^{2/3} \left(\frac{r_{\rm L}}{10^{14}{\rm cm}}\right)^{2/3}. \tag{4}$$

2.3. Expected TeV characteristics

The above considerations suggest that electron acceleration close to the central BH in Cen A may produce Lorentz factors $\gamma \sim 10^7$. This would allow Thomson inverse Compton upscattering of ambient disk photons to TeV energies of $\epsilon \sim \gamma m_e c^2 \simeq 5\, (\gamma/10^7)$ TeV. The resultant TeV spectral index at the high energy end then traces, over a decade or so, the underlying disk seed photon spectrum (Rieger & Aharonian 2008b). In the ADAF case, comptonization of thermal synchrotron soft photons is expected to lead to a power-law-like tail in the disk spectrum above ν_s, i.e., $L_\nu \simeq L_{\nu_s}(\nu/\nu_s)^{-\alpha_c}$, where $\alpha_c = -\ln \tau_{\rm esc}/\ln A$ depends on the accretion rate (Mahadevan 1997; Yi 1999). For the inferred mass accretion rate of Cen A, $\dot{m} \simeq (2-20) \times 10^{-4} \dot{m}_{\rm Edd}$, the spectral index becomes $\alpha_c \simeq (1.2-1.9)$ assuming a standard ADAF viscosity coefficient $\alpha = 0.3$. This suggests that the upscattered TeV spectrum in Cen A might in fact be softer than that observed in M87 (see Aharonian et al. 2006). A spectral fit to the VHE (> 300 GeV) data obtained by H.E.S.S. indeed suggests a power-law spectral index in the range 1.7 ± 0.5 (Aharonian 2009a). A soft spectrum with, e.g., $\alpha_c = 1.8$, may then indicate

that accretion occurs at the lower end of the concordant interval noted above. Since particle acceleration occurs close to the light surface, the expected minimum TeV variability timescale is $\sim r_L/c \sim 1$ hour.

Is it possible that TeV photons, produced by inverse Compton upscattering, can escape from the vicinity of the central black hole in Cen A? In principle, photons of energy E [TeV] will interact most efficiently with target photons in the infrared regime, i.e., of energy $\epsilon_{IR} \simeq (1 \text{ TeV}/E)$ eV. For the radio luminosity L_R estimated above, the implied infrared (1 eV) ADAF disk luminosity is on the order of $L_{IR} \sim 3 \times 10^{39} (300)^{1-\alpha_c}$ erg/s. The optical depth for $\gamma\gamma$-absorption $\tau_{\gamma\gamma} \simeq (L_{IR}\sigma_{\gamma\gamma})/(4\pi R_{IR}\epsilon_{IR}c)$ thus becomes

$$\tau_{\gamma\gamma}(E, R_{IR}) \sim \frac{4}{300^{\alpha_c-1}} \left(\frac{L_{IR}}{3 \times 10^{39} \text{ erg/s}}\right)\left(\frac{r_L}{R_{IR}}\right)\left(\frac{E}{1 \text{ TeV}}\right), \quad (5)$$

indicating that TeV photons may well escape from the vicinity of the black hole provided the spectrum is sufficiently soft (i.e., for $\alpha \gtrsim 1.4$). The nuclear (pc-scale) region of Cen A, on the other hand, is known to be relatively mid-infrared-bright (with luminosity of $\sim 7 \times 10^{41}$ erg/s). Yet, if this flux is indeed dominated by emission from a dusty torus of size $\gtrsim 0.1$ pc (see Radomski et al. 2008), VHE gamma-rays would also be able to escape unabsorbed from the nuclear region of Cen A.

One can estimate the maximum possible TeV luminosity output $L_{IC} \sim \rho \, n \, P_c \, \Delta V$ based on the Alfvén corotation condition $B^2/8\pi \geq n\gamma m_e c^2$, which provides an upper limit for the accelerated particle number density close to r_L. By noting that for the relevant volume one has $\Delta V = 4\pi(\gamma_0/\gamma)r_L^3$, that P_c can be approximated by the single particle Thomson power, and that particles are accumulated for $\rho = t_{cool}/t_{acc} \geq 1$ (correcting a typo in RA08a, eq. 12), the maximum possible inverse Compton TeV luminosity is of order

$$L_{IC}^{TeV} \sim 10^{39} \left(\frac{B(r_L)}{50G}\right)^2 \left(\frac{r_L}{1.5 \times 10^{14}\text{cm}}\right)^2 \left(\frac{\gamma_0}{10}\right)^{1/2} \left(\frac{10^7}{\gamma}\right)^{1/2} \text{ erg/s}, \quad (6)$$

which is consistent with the H.E.S.S. results of Aharonian et al. (2009a). Since L_{IC} increases almost linearly with black hole mass, a source needs to be sufficiently massive to become detectable by current ground-based instruments. In fact, under normal conditions (i.e., for moderate injection Lorentz factors $\gamma_0 \sim 10$), the inferred TeV output for Cen A is close to the sensitivity limit (1% of the Crab flux, with 5σ in 50h) of the H.E.S.S. array. Variability studies on hour timescale will thus only be possible with the next-generation CTA telescope project.

3. On Cen A as a possible UHECR proton source

According to the Pierre Auger results, 4 out of 27 events detected above 57 EeV may be associated with the location of Cen A (Abraham et al. 2007, 2008). If some of these cosmic ray events were indeed associated with Cen A, it seems unlikely that their energization could occur close to the central BH. Neither a Blandford-Znajek-type nor a centrifugal disk wind scenario seems to allow for that: For example, if the black hole in Cen A rotates and is embedded in a magnetic field of equipartition strength $B_0 \lesssim 10^4 (\dot{m}/10^{-2}\dot{m}_{Edd})^{1/2}(10^8 M_\odot/m_{BH})^{1/2}$ G, it could act as a unipolar inductor (membrane paradigm) and induce a voltage difference of the order of

$$\Phi \sim 4 \times 10^{19} Za \left(\frac{m_{BH}}{10^8 M_\odot}\right)\left(\frac{B_0}{10^4 G}\right) \text{ V}. \quad (7)$$

However in reality, it seems unlikely that protons might be able to fully tap this potential. Even if the ordered magnetic field component could be as high as B_0, screening of the electric field in the plasma-rich AGN environment and curvature losses, for example, are readily expected to reduce achievable proton energies to below $\sim 10^{19}$ eV (cf. Levinson 2000; Aharonian et al. 2002). Moreover, as an FR I source, Cen A is most likely characterized by a Kerr parameter a well below one (e.g., Daly 2009). Centrifugal acceleration of particles in the rotating disk magnetosphere, on the other hand, is limited by the condition for single particle corotation, cf. Eq. (4). While this works well for electrons, efficient centrifugal acceleration of protons to energies far beyond 10^{17} eV is unlikely to occur in the vicinity of the central BH. We finally note, that the required Lorentz factors of $\gamma_p \gtrsim 5 \times 10^{10}$ (if assumed to be protons) would already imply a gyro-radius $r_{gyro} \simeq 1.5 \times 10^{15}(\gamma_p/5 \times 10^{10})$ (100 G/$B(r_L)$) cm, exceeding the characteristic light cylinder scale for Cen A.

Furthermore, if radio observations are a reliable tracer of the true fluid speeds in the jet of Cen A, internal shocks are also probably not able to account for UHECRs beyond 50 EeV. On both VLBA subparsec-scales and VLA scales of hundreds of parsecs, the jet bulk speed seems to be at most mildly relativistic, not exceeding 0.5c by much (Tingay et al. 2001; Hardcastle et al. 2003). If the shocks are internal with characteristic speeds comparable to the relative velocity between layers, shock speeds β_s well below 0.5c are expected. Balancing the minimum timescale for non-relativistic shock acceleration (Bohm limit, e.g. see Rieger et al. 2007) with the timescale for cross-field diffusion then implies, that possible cosmic ray energies are limited to $E_{max} \simeq Z e B r_t \beta_s$, where r_t is the (transverse) source size and B the local magnetic field strength. Even if one would allow for some local magnetic field amplification by a factor ρ (e.g., due to shock compression or shear-driven instabilities) and assume that radiative losses could be neglected, possible proton energies are unlikely to exceed

$$E_{max} \lesssim 2 \times 10^{19} \rho_4 \left(\frac{B_0}{10^4 \text{ G}}\right) \left(\frac{\beta_s}{0.1 \text{ c}}\right) \text{ eV}, \quad (8)$$

where the strength of the local field at $r \sim r_t/\alpha_j$ (where α_j is the jet opening angle) has been expressed as $B \simeq \rho B_0 (r_s/r)$, $\rho_4 = \rho/4$, with e.g., $\rho_4 = 1$ for a strong shock-compressed downstream region. While it seems thus unlikely that protons can be accelerated to 50 EeV and beyond (at least if no dramatic flaring activity is assumed, cf. Dermer et al. 2009), acceleration to the ankle at $\sim 4 \times 10^{18}$ eV might well be possible.

Hardcastle et al. (2009) recently proposed that efficient stochastic particle acceleration could occur in the giant radio lobes of Cen A on scales of $R \sim 100$ kpc. In the Bohm limit, the characteristic acceleration timescale for stochastic second order Fermi acceleration is of order $t_{acc} \simeq (c/v_A)^2(r_{gyro}/c)$ (e.g., Rieger et al. 2007). Comparing this timescale with that for cross-field diffusion, i.e., $t_{df} \sim 3R^2/(cr_{gyro})$, suggests that proton energies are limited to

$$E_{max} \simeq 1.6 \times 10^{19} \left(\frac{v_A}{0.1 \text{ c}}\right) \left(\frac{R}{100 \text{ kpc}}\right) \left(\frac{B}{10^{-6} \text{ G}}\right) \text{ eV}. \quad (9)$$

Hence, if relativistic turbulent wave speeds can be achieved (of order $v_A \simeq 0.3c$, as assumed in Hardcastle et al. 2009), proton acceleration to energies 5×10^{19} eV could become possible. Yet, whether these conditions exist, seems unclear (cf. O'Sullivan et al. 2009). If (part of) the observed X-ray emission from the giant lobes is produced by thermal plasma emission, the implied thermal plasma density would be of order $n_{th} \sim (10^{-5} - 10^{-4})$ cm^{-3},

i.e., much higher than conducive to fast Alfvénic turbulence. For typical equipartition field strengths of $B \sim 10^{-6}$ G, the characteristic Alfvén speed $v_A \simeq B/\sqrt{4\pi\,n_{\rm th}\,m_p} \lesssim c/500$ would be much lower than required.

Based on the above considerations, it seems questionable whether protons could indeed be accelerated to energies beyond 10^{19} eV in Cen A. However, one possible mechanism that may help particles to reach beyond this limit could be shear acceleration along the large-scale jet (Rieger & Duffy 2004). Strong internal jet stratification (e.g., a fast spine surrounded by slower moving layers) is naturally expected for jets interacting with their environments or launched by different processes (e.g., disk and black-hole driven wind), and indeed seen in hydrodynamical simulations (e.g., Meliani & Keppens 2007; Aloy & Mimica 2008). In the case of Cen A, there are some observational hints, e.g., limb-brightening in the X-ray jet, the higher energy emission being more confined to the jet axis, longitudinal magnetic field polarization in the large-scale jet (Kataoka et al. 2006; Kraft et al. 2002; Hardcastle et al. 2003) that might be indicative of internal jet stratification. Energetic particles scattered across such a shear flow can sample the kinetic difference in the flow and be accelerated to higher energies. The timescale for particle acceleration in a continuous shear flow is inversely proportional to the particle mean free path $t_{\rm acc} \propto 1/\lambda$ (Rieger & Duffy 2004). In order to compete with radiative losses, and in the case of Cen A with advection along the jet, high energy seed particles are thus needed to ensure efficient particle acceleration. Assuming a gyro-dependent particle mean free path $\lambda \sim r_{\rm gyro}$, the minimum acceleration time scale in a linearly decreasing velocity shear profile is on the order of $t_{\rm acc} \simeq 3(\Delta r)^2 c/[\lambda\,\gamma_b^4(\Delta v_z)^2] \sim 6\,(\Delta r)^2/(r_{\rm gyro}c)$ assuming $v_z \sim 0.5c$ (see Rieger & Duffy 2004). Advection along the jet occurs on a characteristic timescale $t_a \sim l_j/v_z \sim 10^{12}$ sec, where $l_j \sim 4.5$ kpc is the (projected) X-ray jet length (Hardcastle et al. 2007). The observed kpc radio jet slightly expands and has a transverse width of ~ 1 kpc close to its end (Kraft et al. 2002). Protons injected at the crossover to the kpc-scales, for example, would thus need seed energies of $E \sim (1-5) \times 10^{18}$ eV to ensure that shear acceleration can operate efficiently (using, e.g., $\Delta r \sim 0.2$ kpc, $B \sim 10^{-4}$ G). Such energetic seed particles may well be provided by e.g. shock acceleration. In this case, protons escaping from the inner shock region and diffusing into the outer shear layers will naturally experience an additional increase in energy. In 3d-hydrodynamical simulations (Aloy et al. 1999), the shear layer is found to broaden with distance along the jet, eventually becoming comparable to the beam width. If one thus takes $\Delta r \sim 1$ kpc near to the jet end (we note that the full width of the turbulent shear layer may be even larger than that seen in the radio), the classical Hillas confinement condition would constrain maximum protons energies to be $E \simeq 10^{20}(B/10^{-4}{\rm G})$ eV. This value might be somewhat higher, if the magnetic field is amplified in the shear (e.g., due to Kelvin-Helmholtz-driven shear instabilities, see Zhang et al. 2009). On the other hand, for smaller transverse shear widths, non-gradual shear acceleration (Ostrowski 1998; Rieger & Duffy 2004) is expected to take over earlier, leading to similar maximum energy considerations but different spectral characteristics.

4. Conclusions

If Cen A hosts a radiatively inefficient inner accretion disk, efficient electron acceleration in its BH-jet magnetosphere and inverse Compton upscattering of ambient disk photons to the TeV regime appears to be possible. After M87, Cen A could thus be another primary candidate source in which VHE processes close to the black hole may allow a fundamental diagnosis of its immediate environment, offering important insights into the central engine in AGNs.

Whether Cen A indeed proves to be an UHECR emitting source may require confirmation by additional observations. From a theoretical point of view and based on conventional acceleration concepts, it seems challenging to account for a possible production of UHECR protons beyond 10^{19} eV. On the other hand, as shown above, shear acceleration along the large-scale jet in Cen A may help to overcome this problem by increasing the energy of shock-accelerated seed particles by a factor of some tens. If this would be the case, spectral changes in the cosmic ray spectrum might be partly due to the operation of a new acceleration mechanism and not simply propagation effects.

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